X-BAND AND K-BAND LUMPED WILKINSON POWER DIVIDERS WITH A MICROMACHINED TECHNOLOGY

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Abstract- **With a novel micromachined technology, Wilkinson power dividers have been realized by lumped components such as spiral inductors, metal-insulator-metal (MIM) capacitors and thin-film-resistors (TFRs). For the first time, X-band and K-band power dividers with low loss (0.6 dB) and wide bandwidth (25% bandwidth for 15 dB return loss) have been demonstrated in this work. Due to the process compatibility, this technology is suitable for Si-based MMIC applications.**

I. INTRODUCTION

In many microwave applications such as power amplifiers, mixers and antenna systems, power dividing/combining is required. An n-way hybrid power divider [1] was first presented by J. Wilkinson in 1960, and it has been widely used for microwave circuits. Since the physical dimension of the standard Wilkinson power divider is proportional to the wavelength of the center frequency, its size becomes prohibitively large and drives MMIC chip larger size and higher cost. At lower frequencies, lumped designs [2]-[3] have been demonstrated which implement the power dividers by utilizing π networks to replace the $\lambda/4$ sections. However, due to the low quality factor (Q) and low resonant frequencies (f_{res}), these circuit demonstrations have been confined to frequencies up to a few GHz. Use of similar lumped designs requires high-performance lumped components in order to make divider performance compatible to distributed dividers up to X-band or even K-band frequencies. In this paper, a novel micromachined structure is applied to lumped inductors to improve the resonant frequency, Q-factor and linearity of the spiral inductor. These micromachined spiral inductors are then used to design Wilkinson power dividers at X-band and K-band and demonstrate lower insertion loss and wider bandwidth.

II. IMPLEMENTATION OF MICROMACHINED SPIRAL INDUCTORS

Lumped components required for the Wilkinson power dividers include resistors, capacitors and inductors. As frequency increases, the behavior of the lumped components, especially for the spiral inductors, is affected by parasitics and results in less linearity and higher loss. To be able to achieve low loss, wide bandwidth at higher frequencies, components with higher resonant frequency, improved Q-factor and linear behavior with frequency are required.

Figure 1 shows the equivalent circuit for a spiral inductor, where L is the inductance and R_s is the resistance due to conductor losses and dissipation from the induced eddy currents in the substrate. The parasitic capacitances in between spiral loops and between the spiral loops and ground are presented by C_0 and C_p. From the equivalent circuit, the admittance matrix parameter $1/Y_{11}$ and Q-factors are given by

$$\frac{1}{Y_{11}} = \frac{R_s}{(1-\omega^2 LC)^2 + \omega^2 R_s^2 C^2} + j\omega\frac{L(1-\omega^2 LC) - R_s^2 C^2}{(1-\omega^2 LC)^2 + \omega^2 R_s^2 C^2} \quad (1)$$

and

$$Q = \frac{Im\left(\frac{1}{Y_{11}}\right)}{Re\left(\frac{1}{Y_{11}}\right)} = \frac{\omega L}{R_s} - \frac{\omega^2 LC}{R_s} - \omega R_s C \quad (2)$$

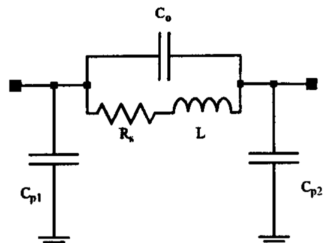


Fig. 1 The equivalent circuit of the spiral inductor.

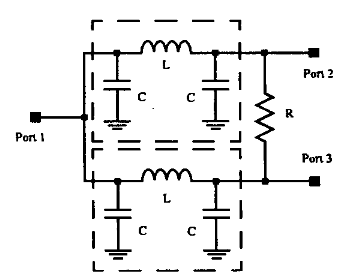
where $C=C_o+C_p$. At lower frequencies, the quality factor can be approximated by $\omega L/R_s$, and its value first increases with frequency. However, the second and third terms in Equation (2) dominate at higher frequencies and cause Q to decrease with increasing frequency. Since the roll-off of the Q-factor is caused by higher frequency parasitics, one effective technique to improve Q and increase resonant frequency is to minimize the parasitic capacitances C_o and C_p. As proposed in [4], a micromachined technology is used to remove the substrate material between the lines, resulting in a reduction of $\varepsilon_{r\text{-}eff}$ for the spiral structure. Thus, both f_{res} and Q of the spiral inductor are improved significantly. In this work, spiral inductors with 15 μm line width, 5 μm spacing and various turn numbers are characterized for high-frequency lumped circuits. Table 1 show the improvement of linearity, Q and f_{res} as a 10 μm micromachined structure is applied.

Table 1. Q-factor and f_{res} of the micromachined spiral inductors

Etch Depth	# of turns	6.5	5.5	4.5	3.5
	L (nH)	7.6	5.0	3.2	1.9
0 μm	Q_{max}	5.7	6	6.3	6.6
	f_{Qmax} (GHz)	2.5	3	5.5	6.5
	f_{res} (GHz)	7.1	9.5	13.5	18.5
10 μm	Q_{max}	12.8	13.6	13.3	15.4
	f_{Qmax} (GHz)	3.5	5.5	6.5	11.5
	f_{res} (GHz)	8.5	11.5	16.9	22.5

III. DESIGN AND FABRICATION

Figure 2 shows the schematic and design parameters of the lumped Wilkinson power dividers with center frequencies of 8.5 GHz and 20 GHz, where L and C are given by $L = \sqrt{2}(Z_o/\omega)$ and $C = 1/(\sqrt{2}\omega Z_o)$. The fabrication of the Wilkinson power dividers herein starts with a high resistivity Si substrate with a resistance of 2000 Ω-cm. A PECVD oxide layer with a thickness of 0.3 μm is deposited as the isolation layer between the substrate and the first metal layer (M1), which is used as the lower plate for MIM capacitors and the underpass contact to return the inner terminal of the coil to the outside. A 0.25 μm-thick PECVD oxide and a patterned Ti/Au metal layer are used to define the area for MIM capacitor. After an 1 μm-thick inter-metal dielectric grown by PECVD, a NiCr layer with a thickness of 700 Å is deposited for TFR. The spiral loops and interconnection are formed by the second metal layer (M2). Both M1 and M2 are evaporated Al layers with thickness of 1 μm and 3 μm, respectively. At this point, standard CMOS processing steps have been used to fabricate the inductors. To apply the micromachined structure to the spiral inductor, the metal layers are covered by a 0.1-μm-thick Ni layer which is then used as self-aligned etch



f_o	L (nH)	C (pF)	R (Ω)
8.5 GHz	1.34	0.27	100
20 GHz	0.56	0.11	100

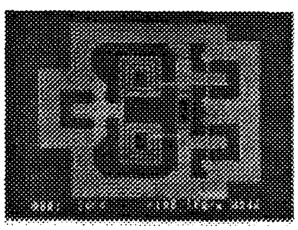
Fig. 2. The schematic of the lumped Wilkinson power divider and the design parameters.

mask. Finally, a deep trench created by RIE using SF_6 and O_2 completes the fabrication process. The photomicrograph of the lumped Wilkinson power dividers are shown in Fig. 3.

IV. Results and Discussion

On-wafer probing of the Wilkinson power divider is performed using HP8510B network analyzer, and the S-parameter measurement covers frequency range from 0.5 GHz to 25.5 GHz. Figure 4 shows the S-parameter measurement for 8.5 GHz and 20GHz design. For both X-band and K-band design, an excess loss better than 0.6 dB at center frequencies is obtained for -3dB coupling while the return loss is better than 15 dB for a bandwidth of 25%. Due to the use of high-Q spiral inductors, the loss introduced by the lumped Wilkinson power divider is even lower than some distributed designs [5]-[6]. The performance of the X-band and K-band Wilkinson power dividers is concluded in Table 2.

One of the most important reasons of using lumped design is the smaller chip size. Using lumped components to replace λ/4 section



(a)

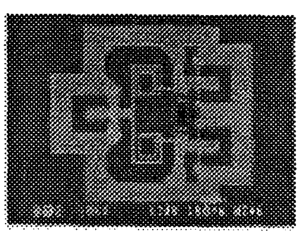


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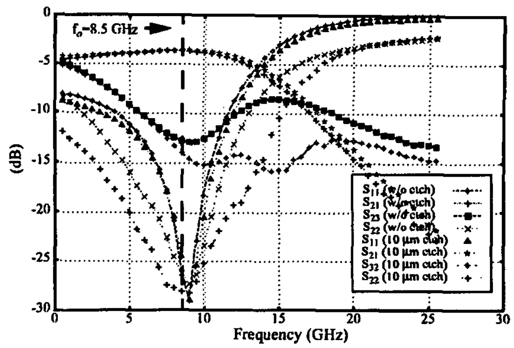
Fig. 3 (a) The photomicrograph of the X-band Wilkinson power divider (chip size = 850 × 700 μm) and (b) K-band power divider (chip size = 750 × 700 μm).



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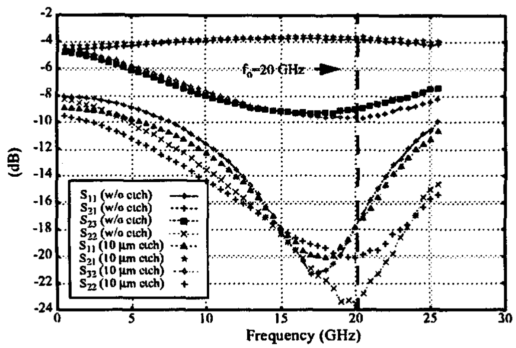

(b)

Fig. 4 (a) The S-parameters of the X-band Wilkinson power divider and (b) the S-parameter of the K-band design.

which is around 4 mm on Si substrate at 8.5 GHz, the chip size of the X-band design including ground and probing pads is 850 × 700 μm. The area required of the divider itself can even be smaller (less than 300 × 400 μm) when integrated with other microwave circuits.

Other than a smaller chip size, wider bandwidth is also the advantage of the lumped design over standard Wilkinson power divider which is limited by quarter wave length requirement. However, the advantage of broadband characteristics for a lumped design is compromised by the poor linearity of passive components. The validity of replacing the λ/4 section by π network is based on a constant reactance $(\omega L = \sqrt{2}Z_o)$ and susceptance $(\omega C = 1/(\sqrt{2}Z_o))$. Due to the finite f_{res}, the inductance and capacitance increases at higher

Table 2. Performance of the power divider.

fo (GHz)	Etch depth (μm)	S_{11} (dB)	S_{22}, S_{33} (dB)	S_{21}, S_{31} (dB)	S_{23} (dB)
8.5	0	-25.9	-26.2	-3.67	-12.8
	10	-24.5	-28.1	-3.57	-14.1
20	0	-17.8	-17.9	-3.81	-9.0
	10	-23.5	-20.1	-3.60	-9.6

frequencies, and it is especially significant for spiral inductors with low f_{res}. The nonlinearity of L and C values reduces center frequency and results in a reduction of bandwidth. By applying the micromachined technology, the spiral inductor can be operated linearly to higher frequencies with an enhanced Q-factor. Therefore, it has a direct impact on the circuit performance in terms of insertion loss and bandwidth.

Due to the finite Q-factor of the inductor components, the insertion loss is 0.6 dB higher than a lossless Wilkinson power divider, and it can, however, be improved by including more metal for low ohmic loss. For a fixed metal thickness, the insertion loss can be further reduced by increasing the line width for the spiral inductors. However, it will cause an increase of the chip size. Therefore, trade-off has to be made between chip size and loss depending on the circuit requirements for specific applications.

V. CONCLUSION

With a micromachined structure, the resonant frequency and the Q-factor of the spiral inductor can be improved significantly. Integrating the micromachined spiral inductors with MIM capacitors and NiCr thin film resistors, the X-band and K-band Wilkinson power dividers are designed and fabricated. To the best of our knowledge, this is the first demonstration of the lumped power divider operating up to X-band and K-band with low insertion loss and wide bandwidth. Since the fabrication process is compatible with SiGe/Si HBT technology, the power dividers can be integrated with active devices for Si-base MMIC applications.

ACKNOWLEDGEMENT

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